Bale Compression and Hydrogen Phosphide Fumigation to Control Cereal Leaf Beetle (Coleoptera: Chrysomelidae) in Exported Rye Straw

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ABSTRACT Control of larvae and adults of cereal leaf beetle, *Oulema melanopus* (L.), by bale compression and hydrogen phosphide fumigation was studied in rye straw, *Secale cereale* L., in Aurora, OR. Natural mortality of larvae after transport was 4.0 ± 1.0% (mean ± SEM). Compression (105 kg/cm^2) of larvae in standard bales (122 cm long) of rye straw resulted in 100% mortality. Compression of adults in standard bales plus storage of the compressed bales (56 cm long) for 1 d in a freight container resulted in 100% mortality. A KD_{50} of 102 ppm hydrogen phosphide for 1 h was estimated from the probit regression line developed from dose–response data at 21°C in basic laboratory tests. The LD_{50}s and LD_{99}s were 163 and 6,910 ppm for 2-h exposures and were 18 and 42 ppm for 6-h exposures at 21°C, respectively. A tested dose of 400 ppm for 24 h at 21°C resulted in 100% mortality of the adults. Larvae (n = 10,560) and adults (n = 18,602) did not survive exposure to bale compression followed by hydrogen phosphide fumigation (60 g/28.3 m^3) for 3 d in rye straw loaded in freight containers in large-scale tests. Copper plate corrosion values indicating the severity of exposure to hydrogen phosphide were 13 and 12, and mean temperatures of five locations in the freight container were 25 and 26°C in large-scale tests with the larvae and adults, respectively. Hydrogen phosphide concentrations were ≥400 ppm throughout the 3-d fumigation for larvae and during the first day of fumigation for adults. We propose that cereal leaf beetle can be controlled by a single treatment of bale compression followed by a 1-d storage period or by a fumigation in which 400 ppm hydrogen phosphide is maintained for 1 d at 21°C or above. We confirmed that a multiple quarantine treatment of bale compression followed by a 3-d fumigation will control cereal leaf beetle in exported rye straw.

KEY WORDS *Oulema melanopus*, rye straw, quarantine

CEREAL LEAF BEETLE, *Oulema melanopus* (L.), was first found in the United States in 1962 (Castro et al. 1965) and recently found in certain regions of Oregon and Washington (Bai and Worth 2001, Bai et al. 2000, Hitchcox et al. 2000). The adult and larval stages of the pest feed on small-grain crops and the damage can cause economic losses. Preharvest control efforts are primarily based on the release of natural enemies (Plant Protection and Quarantine 1995). The most successful have been the egg parasite *Anaphes flavipes* (Foerster) (Maltby et al. 1971) and the larval parasite *Tetrastichus julis* (Walker) (Stehr 1970). Cereal leaf beetle may occur in areas where rye straw, *Secale cereale* L., is produced. Rye straw exported to foreign countries is a valuable export commodity from the western states. A postharvest quarantine treatment will ensure that rye straw exports would not be jeopardized by the occurrence of the pest.

Research to develop quarantine treatments for exported hay have been based on control of Hessian fly, *Mayetiola destructor* (Say), using a combination of bale compression and hydrogen phosphide fumigation (Yokoyama et al. 1993a,b, 1994a,b, 1996, 1999). The multiple quarantine treatment to control Hessian fly has been approved and implemented by hay exporters since 1996 (Yokoyama et al. 1996, 1999). Therefore, costs to modify treatment procedures to control any new postharvest pest such as cereal leaf beetle would be minimal.

Basic studies are needed to determine the effect of bale compression on survival of cereal leaf beetle inside standard bales and to determine the effect of storage on insect survival inside compressed bales. Basic laboratory tests are needed to determine the response of cereal leaf beetle to hydrogen phosphide fumigation. Development of a multiple quarantine treatment using bale compression and hydrogen phosphide fumigation would require large-scale testing that would simulate commercial conditions and testing of large numbers of insects.

[1] This article reports the results of research only. Mention of a proprietary product does not constitute an endorsement or recommendation by USDA for its use.

The objective of this study was to determine in basic laboratory and large-scale commercial tests, the efficacy of bale compression alone, bale compression plus storage, hydrogen phosphide fumigation alone, and a combination treatment of bale compression and hydrogen phosphide fumigation to control cereal leaf beetle in exported rye straw.

Materials and Methods

Source of Insects and Location of Test Facility. Test insects were collected by cooperators from the USDA Animal and Plant Health Inspection Service, Plant Protection and Quarantine (APHIS, PPQ), Cheyenne, WY, and Helena, MT, Collections were made in Cody, WY, and in Frenchtown, Huson, and Huntley, MT, from June through July 2000. Collections were made in Banks, OR, in cooperation with the Oregon Department of Agriculture. Cereal leaf beetle larvae and adults were collected from commercial fields of barley, oats, wheat, corn, and wild grasses.

Larvae were collected on host material, counted, and placed in covered 480-ml (9 cm diameter by 9.7 cm high) paper cartons or plastic containers (9 cm wide by 23 cm long by 27 cm high). The top of the paper carton was covered with cotton organdy or fiberglass screen with a water-moistened sponge placed on the top. A plastic petri plate cover was placed over the top of the sponge and secured to the bottom of the carton with a rubber band. Plastic containers were covered with a water-moistened adsorbent towel that was secured in place with rubber bands. Adults were collected with sweep nets and held in containers similar to those used for larval collections. The insects were refrigerated or cooled with gel refrigerant in styrofoam boxes until used. Numbers of insects tested in each experiment were based on the availability of collected material.

A temporary laboratory (2.4 m wide by 6.1 m long) (Williams Scottsman, Portland, OR) with a thermostat-controlled heating and cooling system was placed at a hay handling and compression plant in Aurora, OR (Anderson Hay and Grain, Aurora, OR). All cereal leaf beetle collections were delivered to this site during this investigation.

Basic Compression Tests. Cereal leaf beetle adults or first through fourth instars were placed in cotton organdy bags (≈31 cm wide by 31 cm long). The bags were sewn on three sides with a seam in the middle to form two compartments. Pink flagging tape was sewn on one corner to facilitate recovery of the bags after treatment. Each bag contained either larvae on the host plant or adults from each shipment. Insects were placed in each compartment and the opening was folded and stapled closed.

Mortality of larvae caused by handling for 1 d was determined by sampling infested host material from each shipment and placing the samples evenly among eight bags in a control. The bags did not have a middle seam. The controls were misted with water and held on gel refrigerant until evaluated. The number of dead and live larvae in each bag (23–69 total per bag) in the control was counted after 24 h. Percentage control mortality for basic compression tests was reported as the mean ± SEM of the eight bags. The total number of larvae tested in basic compression tests was multiplied by the percentage mortality in the control and that product was subtracted from the total number tested.

Three bags of either larvae or adults were prepared for each standard test bale (≈41 cm wide by 58 cm high by 122 cm long) of rye straw. One bag was placed near the front (closest to the hydraulic ram), one bag was placed in the middle, and one bag was placed toward the back of a standard bale before the bale was compressed. Four bales were prepared with bags containing larvae (≈171 larvae per bag) and eight bales were prepared with bags containing adults (25–513 adults per bag) to determine the effect of compression alone on insect mortality. Four bales were prepared with bags containing either larvae (≈171 larvae per bag) or adults (29–160 adults per bag) to determine the effect of compression plus storage for 1 d in a freight container on insect mortality.

In tests to determine the effect of compression alone on insect mortality, four rye straw bales containing larvae and eight bales containing adults were compressed (105 kg/cm^2) in a commercial hay compressor (Double Compressed, Hemet, CA). The bales were opened immediately after compression and the bags were removed. The bags were cut open, the appearance of the larvae observed, and the contents of the bag inspected for live larvae. The adults were observed for damage and the number of live and dead insects were counted in each bag.

In tests to determine the effect of compression plus storage for 1 d in a freight container (2.4 m wide by 12.2 m long by 2.9 m high) on cereal leaf beetle mortality, four rye straw bales containing larvae and four bales containing adults were compressed and placed in separate freight containers for each life stage. The bales containing bags were placed at random, one bale per each of four tiers in the third row (five rows of 16 bales per row, four bales wide by four bales high) of the freight container. The first and second row and the fourth and fifth row in the freight container were composed of rye straw bales without bags of insects. Temperature loggers (model XTI08, Stowaway, Logan, UT) with external thermistors (17 mm long by 3 mm diameter) on extension cables (1.8 m long) and relative humidity loggers (model SRHA08, Stowaway, Logan, UT) were placed at random in the top three tiers of the third row. One of each type of logger was placed in each tier. The temperature thermistors were placed in the interior of the bales through stainless steel tubing driven into the bales.

Basic Fumigation Tests. Basic fumigation test procedures were similar to those described by Zettler et al. (1989). Cereal leaf beetle larvae (75) or adults (51–950) were placed in a 2,600-ml glass desiccator (model 3118–160, Corning, Big Flats, NY) with an external sleeve. Plastic tubing with a pinchcock clamp and a luer connector were attached to the sleeve of the desiccator.

Hydrogen phosphide (5,180 ppm) was dispensed through a luer stopcock attached to a two-stage gas regulator on a compressed gas cylinder (phosphine, Matheson Gas Products, Newark, CA). Gas-tight syringes (Hamilton, Reno, NV) with luer fittings were used to transfer dosages from the gas cylinder to the glass desiccators containing test insects. Each concentration (5–400 ppm) and duration (1–40 h) tested was replicated three times. Fumigations were conducted in the temporary laboratory in which temperatures were recorded with a hygrothermograph and reported as the mean ± SEM of the daily low and high temperatures during the basic fumigation tests. The desiccator lids were removed in open air for aeration at the end of the exposure period. The insects were held in the temporary laboratory at an ambient room temperature of ≈21°C until they were evaluated.

Insect knockdown (KD) was determined by loss of locomotion immediately after exposure to the fumigant. Insect mortality was evaluated 0–18 h after exposure and was determined by inactivity and loss of leg movement in larvae and loss of leg and antennal movement in adults. Insects were reevaluated 18–64 h after treatment to determine if they recovered. Three replicates of insects (289–621 per replicate) were held in desiccators and not exposed to the fumigant to determine control mortality for each exposure period tested. The data for the controls and the concentrations tested for each duration were analyzed by the POLO computer program (LeOra Software 1987) to determine KD_{50}s, LD_{50}s, LD_{99}s, and their respective 95% CLs.

Large-Scale Compression and Fumigation Tests. Large-scale tests were conducted according to techniques previously described by Yokoyama et al. (1996) to develop a multiple quarantine treatment for Hessian fly. Approximately 11,000 cereal leaf beetle larvae were collected on barley in Cody, WY, and shipped to Aurora, OR. Cloth bags (33 cm wide by 33 cm long) were sewn with a center seam to form two pockets and with pink flagging tape attached to one corner. The larvae on leaves and shoots of barley were divided and placed into each of the two pockets of 45 bags.

In a separate large-scale test, 18,904 cereal leaf beetle adults were collected in Banks, OR, and collected and shipped from Billings, MT, and Cheyenne, WY, The adults were divided and placed into each of two pockets of 45 bags.

Natural mortality of the larval stage during handling and transport was determined by sampling (8 replicates of 20–156 larvae per replicate) the infested host material from each shipment of larvae, counting the total number of dead and living insects, and reporting the results as the mean ± SEM percentage natural mortality. The total number of larvae tested in the large-scale compression and fumigation test was corrected for natural mortality by multiplying the percentage natural mortality times the total number tested and subtracting the product from the total number tested.

Adult control mortality was determined from six replicates of adults (97–232 per replicate) that were held in the laboratory for 3–4 d and were not exposed to compression and fumigation. Percentage mortality in the control was reported as the mean ± SEM of the six replicates and multiplied times the total number of adults tested. The product was subtracted from the total number of adults to obtain the corrected total.

Three bags of larvae or adults were compressed in each of 15 standard bales of rye straw. Each bale was considered a replicate and three replicate bales were used for each of five positions in the freight container: front top, front bottom, middle bale, back top, and back bottom. The freight containers were loaded with 26 rows of 16 bales per row. Rows 1, 13, and 26 (adjacent to the doors) were considered the front, middle, and back of the freight container.

A copper plate to detect hydrogen phosphide was compressed in each of five bales. One bale containing a copper plate only was placed in each of the five positions in the freight container among the bales containing bags of insects. A copper plate was placed in the middle of the right door of the freight container. Copper plates were evaluated for severity of corrosion caused by exposure to hydrogen phosphide using the following scores: 3, severe; 2, moderate; 1, light.

Temperatures were determined every 6.5 min during the test with temperature loggers that had external thermistors on extension cables placed in the interior of the bales through stainless steel tubing. Temperatures were recorded in one bale in each of the five positions in the freight container and in the middle air space.

Gas lines were placed in bales in each of the five positions in the freight container among the bales containing test materials and in the middle air space. Gas concentrations were determined each day for 3 d after the beginning of fumigation. Fumigant concentrations were determined with hydrogen phosphide 50/a tubes (model CH 21201, Drager Rohrchen, Germany).

The compressed bales of rye straw in the freight container were fumigated for 3 d with 60 g aluminum phosphide per 28.3 m^3 in tablet prepacs in a secured yard. After fumigation, the freight container was aerated overnight and unloaded when hydrogen phosphide concentrations were ≤0.3 ppm (Degesch America 1990). The test materials were recovered and insect mortality determined.

Results and Discussion

Cereal leaf beetle adults and larvae showed good viability after collection and transport from Oregon, Montana, and Wyoming to our temporary laboratory in Aurora, OR. Natural mortality of larvae in these shipments was 4.0 ± 1.0% (mean ± SEM). Cereal leaf beetle larvae and adults are the only life stages that may require treatment in exported hays because the eggs are fragile (Guslits 1987) and the pupae are found in earthen cells in the soil (Plant Protection and Quarantine 1995).

Table 1. Mortality of cereal leaf beetle larvae and adults in standard bales of rye straw after exposure to compression (105 kg/cm^2) alone or compression plus storage for 1 d in freight containers partially loaded with compressed bales at ambient temperature and relative humidity (mean ± SEM)

Life stage	Treatment	n	% mortality	Temp, °C	% RH
Larvae	Compression	1,706	100.0	—	—
	Compression + 1-d storage	1,706	100.0	22.7 ± 0.3	45.4 ± 1.3
Adults	Compression	4,463	99.8	—	—
	Compression + 1-d storage	1,100	100.0	24.8 ± 0.1	50.9 ± 0.3

Standard bales of rye straw exported to countries such as Japan are compressed to increase the amount of hay placed into each freight container and to facilitate handling of large amounts of hay for shipment. Compression (105 kg/cm^2) of cereal leaf beetle larvae in standard bales of rye straw resulted in 100% mortality of the immature stages (Table 1). These insects were recovered and examined immediately after bale compression. They were flattened with ruptured intersegmental membranes. The larvae were soft and covered with fecal material (Castro et al. 1965) and were easily damaged by compression in bales.

Short-term storage of hay in freight containers simulates preshipping conditions. Complete mortality was observed for larvae that were compressed in rye straw bales and stored for 1 d in freight containers which were partially loaded with other bales (Table 1). These larvae were completely desiccated and only the exoskeleton remained. The ambient temperature and relative humidity among the bales in the freight container were compatible for insect development (Castro et al. 1965, Wellso and Hoxie 1981) and were not the cause of larval mortality. Mortality of larvae in controls that were placed in cloth bags and held for 1 d was 17.0 ± 4.0% (mean ± SEM). This level of larval mortality in the controls suggests that the immature stages may be susceptible to damage during routine hay handling procedures such as baling, compression, and shipment in freight containers.

A small number of adults survived compression in standard bales of rye straw (Table 1). Cereal leaf beetle adults are robust. Although the adults were considered "alive" if they showed movement, all survivors had anatomical damage such as broken appendages and could not walk or fly in a normal manner. No adults survived compression in rye straw bales and storage for 1 d in a freight container that was partially loaded with compressed bales. Constant pressure is exerted on insects within the compressed bale after it is tied to prevent the hay from expanding. One day of storage under these adverse conditions resulted in complete mortality of the adults. The temperature and relative humidity inside the freight container was compatible with insect development (Castro et al. 1965, Wellso and Hoxie 1981) and did not cause adult mortality.

We reported that compression reduces the length of a standard bale from ≈91–122 cm to a length of 46–61 cm after it was compressed and tied (Yokoyama et al. 1993b). The length of the rye straw standard bales used in this investigation was reduced from 122 cm to 56 cm in the tied finished bale. Although a higher compressor pressure (105 kg/cm^2) was used compared with our earlier work (80 kg/cm^2) (Yokoyama et al. 1999), the size of the finished bale was similar. High compressor pressure is a manufacturing feature of contemporary compressors which expedites the compression process.

Our results show that bale compression plus storage of the compressed bales in freight containers before shipment would control adult and immature cereal leaf beetle stages inside rye straw bales. Large-scale tests using a large-number of insects should be conducted to confirm the efficacy of this treatment.

Dose–response relationships were developed for cereal leaf beetle adults and hydrogen phosphide at 1-, 2-, and 6-h durations at 21.4 ± 0.3°C (mean ± SEM) (Table 2). Adults appeared to be sensitive to the fumigant and showed uncoordinated leg movements soon after exposure. Adults that had been evaluated for mortality were reexamined up to 64 h after the initial evaluation to verify that no insects recovered from the treatment. Although some individuals were considered "alive" because they showed movement of appendages, these insects could not walk or fly.

Cereal leaf beetle adults were physically impaired after an exposure of 1 h to hydrogen phosphide fumigation at dosages as low as 50 ppm at 21°C. A dosage that would knockdown 50% (KD_{50}) of the test population was estimated from the probit regression line developed from dose–response data at 1-h exposures determined in basic laboratory tests (Table 2). Our results in basic laboratory tests showed that half of the individuals that may occur in rye straw would be immobilized by exposure to 102 ppm of hydrogen phosphide after a 1-h exposure. Such dosages occur in the initial phase of hydrogen phosphide fumigation of hay in freight containers. Rapid knockdown would

Table 2. Response of cereal leaf beetle adults to hydrogen phosphide fumigation at 21°C in basic laboratory tests

Duration h	n	Slope ± SE	KD_{50}, ppm (95% CL)	LD_{50}, ppm (95% CL)	LD_{99}, ppm (95% CL)
1	3,277	3.5 ± 0.1	101.8 (66.0–134.1)	—	—
2	4,248	1.4 ± 0.1	—	163.4 (105.5–269.2)	6,910.1 (1,702.6–886,587.7)
6	4,155	6.2 ± 0.2	—	17.9 (16.3–19.3)	42.2 (37.3–50.2)

Table 3. Response of cereal leaf beetle larvae and adults to different durations of exposure to 400 ppm hydrogen phosphide at 21°C

Life stage	n	Duration, h	% mortality
Larvae	75	3	100.0
Adults	1,581	12	99.1
	2,234	15	99.9
	1,336	24	100.0
	1,233	40	100.0

help immobilize adults for exposure to lethal doses at longer durations during the fumigation process.

Comparisons of the lethal dose to 50% (LD_{50}) and 99% (LD_{99}) of the test populations shows that length of exposure to hydrogen phosphide at 21°C is directly related to cereal leaf beetle mortality (Table 2). A 6-h exposure resulted in a LD_{50} of 18 ppm. A reduction of the exposure period to 2 h resulted in a nine-fold increase in the LD_{50} to 163 ppm. A reduction in exposure from 6 to 2 h resulted in a 164-fold increase in the LD_{99}. Although cereal leaf beetle appears to be quite sensitive to fumigation with hydrogen phosphide, control will require adherence to the specified duration of a proposed treatment to achieve complete control of the pest.

The response of cereal leaf beetle larvae and adults to a tested dose of 400 ppm hydrogen phosphide at 21°C for different durations of exposure is shown in table 3. This differs from Table 2 in which relative dosage values (KD_{50}, LD_{50}, and LD_{99}) were reported from the estimated dose–response statistical probit regression lines developed from dose–response data determined in basic tests. The larval stage was very sensitive to 400 ppm hydrogen phosphide and complete mortality was attained after a 3-h exposure (Table 3). Testing high numbers of adults at 400 ppm for durations of 12 and 15 h resulted in a low number of survivors but less so at the 15-h exposure. Complete mortality of the test populations occurred at 24- and 40-h durations. An estimated dosage of 42 ppm in a 6-h exposure at 21°C was projected to cause 99% mortality of cereal leaf beetle adults (Table 2). Actual testing on adults showed that 400 ppm for 24 h at 21°C was needed for 100% mortality. The difference between estimated (42 ppm for 6 h) and tested (400 ppm for 24 h) dosages for 100% mortality at 21°C may be attributed to natural variation (Robertson and Yokoyama 1998) and the higher number of insects tested at 400 ppm. A concentration of >400 ppm hydrogen phosphide was maintained from day 2 to day 3 in a previous large-scale fumigation of rye straw (unpublished data analyzed in Yokoyama et al 1993a). Our findings support the use of a 3-d hydrogen phosphide fumigation as a single quarantine treatment to control cereal leaf beetle in rye straw if a concentration of 400 ppm is maintained for 1 d. A fumigation period of 3 d will be more economical than the 7-d fumigation that is currently used in the multiple quarantine treatment to control Hessian fly in exported hay.

Cereal leaf beetle larvae and adults did not survive exposure to a multiple treatment of bale compression (105 kg/cm^2) followed by hydrogen phosphide fumigation (60 g/28.3 m^3) for 3 d in rye straw (Table 4). The fumigant dosage was the same as used in the multiple quarantine treatment to control Hessian fly in compressed hay exported to Japan. However, the duration of exposure was reduced from 7 d for Hessian fly to 3 d for cereal leaf beetle. Larvae recovered after treatment in the large-scale test were dead, flattened, and dark in color, or only the exoskeleton remained. In the large-scale test with adults, the insects were crushed and lifeless. The total number of larvae in the large-scale test was 10,560 after correction for natural mortality of 4.0 ± 1.0% (mean ± SEM). In the large-scale test for adults, the total number tested was 18,602 after correction for control mortality of 1.6 ± 0.5% (mean ± SEM).

Table 4. Survival of larvae and adults, copper plate corrosion values, and mean ± SEM temperatures and fumigant concentrations in different locations in a freight container in large-scale tests to confirm the efficacy of compression (105 kg/cm^2) and fumigation (60 g/28.3 m^3 aluminum phosphide for 3 d at ambient temperatures) to control cereal leaf beetle in rye straw

Life stage	Location	No. survivors	Copper plate corrosion[a]	Temp, °C	PH_3 concn, ppm
Larvae[b]	Front top	0	2	27.0 ± 0.03	675.0 ± 118.1
	Front bottom	0	2	25.5 ± 0.05	600.0 ± 87.8
	Middle bale	0	2	23.3 ± 0.07	475.0 ± 38.2
	Middle air	—	—	26.7 ± 0.01	516.7 ± 16.7
	Back top	0	2	24.0 ± 0.03	600.0 ± 80.4
	Back bottom	0	2	22.7 ± 0.05	658.3 ± 104.4
	Door	—	3	—	—
Adults[c]	Front top	0	2	27.9 ± 0.05	341.7 ± 114.6
	Front bottom	0	2	—	308.3 ± 101.4
	Middle bale	0	1	26.3 ± 0.02	291.7 ± 97.1
	Middle air	—	—	25.4 ± 0.02	323.3 ± 102.9
	Back top	0	2	26.9 ± 0.05	296.7 ± 101.0
	Back bottom	0	2	24.6 ± 0.02	295.0 ± 105.0
	Door	—	3	—	—

[a] Degrees of corrosion: 1, light; 2, moderate; 3, severe.
[b] n = 10,560.
[c] n = 18,602.

The sum of the copper plate corrosion values from all locations in the freight container was 13 for larvae and 12 for adults (Table 4). These values are similar to those obtained in a confirmatory test of the multiple quarantine treatment using bale compression and a 7-d hydrogen phosphide fumigation to control Hessian fly at the same dosage (Yokoyama et al. 1999). The corroded copper plates are a visible verification that hydrogen phosphide penetrated the compressed bales in all locations in the freight container during the 3-d fumigation.

Mean ± SEM temperatures in bales in the different locations and in the middle air space of the freight container were 24.9 ± 0.7°C in the large-scale test for larvae and 26.2 ± 0.6°C (mean ± SEM) in the large-scale test for adults (Table 4). The temperature logger in the front bottom bale location in the freight container failed during the large-scale test for adults. The freight containers were held outdoors during the 3-d fumigation. Temperatures in the freight containers were higher than those reported for fumigations in heated buildings (Yokoyama et al. 1996, 1999) that were conducted during cold weather. The recommended temperature for a 3-d fumigation is ≥20°C (Degesch America 1990). Hydrogen phosphide fumigations would be conducted at temperatures similar to those in these tests if completed during the period in which cereal leaf beetle adults are active in the northwestern United States between April and August (Hitchcox et al. 2000, Bai and Worth 2001). Basic laboratory tests showed that a concentration of 400 ppm hydrogen phosphide for 1 d at ≈21°C would control cereal leaf beetle adults without bale compression (Table 3). This concentration could be achieved during fumigations at temperatures shown in these large-scale tests.

Hydrogen phosphide concentrations in the large-scale test with cereal leaf beetle larvae were ≥400 ppm (range, 400–850 ppm) throughout the 3-d fumigation. In the large-scale test with adults, hydrogen phosphide concentrations were >400 ppm (range, 450–515 ppm) during the first day of fumigation and averaged <400 ppm over 3 d. Lower hydrogen phosphide concentrations in the large-scale test with adults in comparison with the large-scale test with larvae may have resulted from leakage of fumigant through the freight container.

The large-scale tests confirmed the efficacy of bale compression (105 kg/cm^2) combined with a 3-d hydrogen phosphide (60 g/28.3 m^3) treatment to control cereal leaf beetle larvae and adults in rye straw. The multiple treatment can be used for quarantine control of cereal leaf beetle in hay to prevent accidental introductions of the pest into areas where it is not found.

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